Optical and VLF Imaging of Lightning-Ionosphere Interactions

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LONG-TERM GOALS

This work addresses some of the key topics of space physics research recommended in the National Research Council 2003 report “A Decadal Research Strategy in Solar and Space Physics”, namely, the thunderstorm-driven electrodynamic coupling between the troposphere, mesosphere, lower ionosphere, and magnetosphere. Lightning-induced electron precipitation encompasses all of these regions, from atmospheric and mesospheric electrodynamics, to radiation belt scattering, to precipitation and disturbances of ionospheric communication channels. Sprites and their possible conjugate effects due to relativistic electrons also constitute a coupling between the regions, including lightning effects on the mesosphere and ionosphere, and relativistic electron beams injected into the magnetosphere. Geomagnetic disturbances highlight the coupling between these regions, with the resulting perturbations in the magnetosphere and ionosphere easily detectable.

OBJECTIVES

Objectives of the current three-year effort are to address the following scientific questions: What role do lightning generated whistlers play in the formation of the slot region of the radiation belts? How can VLF remote sensing be used to quantitatively measure the energy spectra and flux of precipitating electrons associated with LEP events? What is the contribution of MR whistlers and lightning-triggered-plasmaspheric hiss to the loss of electron radiation? How do sprites evolve on a fine spatial and temporal scale, and how does this evolution compare to conventional and streamer breakdown theory? What is the cause of the fine-scale bead-like features of sprites? How does the thundercloud activity relate to the spatial and temporal evolution of sprites? How are sprites and sprite halos related to conductivity perturbations on the ionosphere, observed as early/fast perturbations to VLF transmitter signals?

APPROACH

Our approach consists of the use of optical and wideband VLF/LF measurements to document high altitude optical phenomena and VLF/LF holographic imaging of ionospheric disturbances together with the causative lightning flashes. The VLF/LF antennas are deployed at seven high schools and colleges spread across the United States, with the students and teachers at these schools involved in the program as part of our educational outreach efforts. Observations of sprites are also made in the Midwestern United States using high-speed telescopic imaging, photometric measurements, and

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ELF/VLF measurements of causative sferics. Sprite observations are compared with VLF narrowband and broadband data to establish correlations between sprite features and lightning and ionosphere activity. To quantify the role of lightning-induced whistlers in the loss of electron radiation, accurate estimates of the amount of precipitation (both the temporal profile and spatial extent) induced by a single lightning are made using continuous VLF measurements of the resulting ionospheric disturbances. The key individuals involved are graduate students that are either fully funded under this program or partly funded by an associated NSF grant, ~10% effort of an engineer, and the Principal Investigator. The students are involved in all aspects of the program, including design and construction of equipment and software, deployment, data acquisition and interpretation, as well as educational outreach (for example by providing lectures at the high schools). The engineer is mainly involved in data archiving and increasing data accessibility.

WORK COMPLETED

During the last year, new data acquisition software was installed at all seven sites of the Holographic Array for Ionospheric Lightning (HAIL) research, allowing for extended coverage periods (22 out of 24 hours) and more accurate phase tracking of the VLF signals.

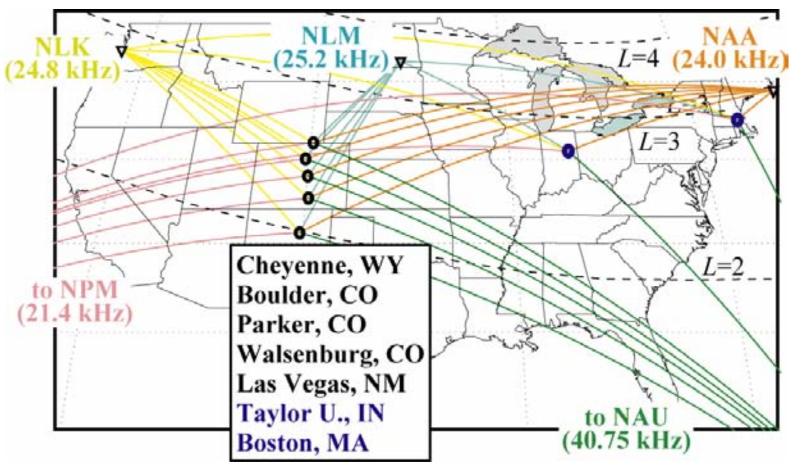

Figure 1: Map showing the coverage area of the HAIL array, 2006.

Measurements with the system are ongoing. A scientific paper published in the Journal of Geophysical Research – Space Physics reported on quasiperiodic mid-latitude ionospheric disturbances, associated with geomagnetic storms, observed on the HAIL array. A second paper submitted to the Journal of Geophysical Research – Space Physics compares VLF experimental observations of LEP events with a comprehensive model of lightning-induced electron precipitation and the resulting ionospheric disturbance, allowing the measurement of such events with unprecedented quantitative detail.

An experiment was conducted in the past year, following on the experiment of 2004, to image sprites at unprecedented spatial and temporal resolution using a high-speed CCD imager mounted on a Dobsonian telescope. While the experiment of 2004 used a camera of only 1000 frames-per-second (fps), this experiment used an intensified camera capable of up to 10,000 fps at better resolution. While the technique and system sensitivity was proven, weather conditions proved unfavorable and no

images of sprite features were obtained. However, wide field-of-view images of sprites from this experiment, together with VLF data, yielded new evidence of a sprite-cloud connection, and those results are under review in Geophysical Research Letters.

RESULTS

The following scientific results were obtained and reported in the indicated papers:

Marshall and Inan [2006a] expanded on a previous paper reporting high-speed telescopic observations of sprite features. In this study, high-speed sprite features were analyzed in terms of sizes and lifetimes. Bead and streamer features were both found to have sizes of ~60 – 300 m, in agreement with previously published results. Lifetimes were only ~1 – 2 ms typically for streamer features, whereas bead features lastly typically ~6 ms, sometimes up to 10's of ms. However, no correlation was found between size and lifetime, as expected. Furthermore, when studied in terms of altitude, both bead and streamer sizes were found to be independent of altitude (over the limited range studied, from 60 – 90 km), while streamer lifetimes were found to increase with altitude, contrary to predictions of E-field persistence versus altitude.

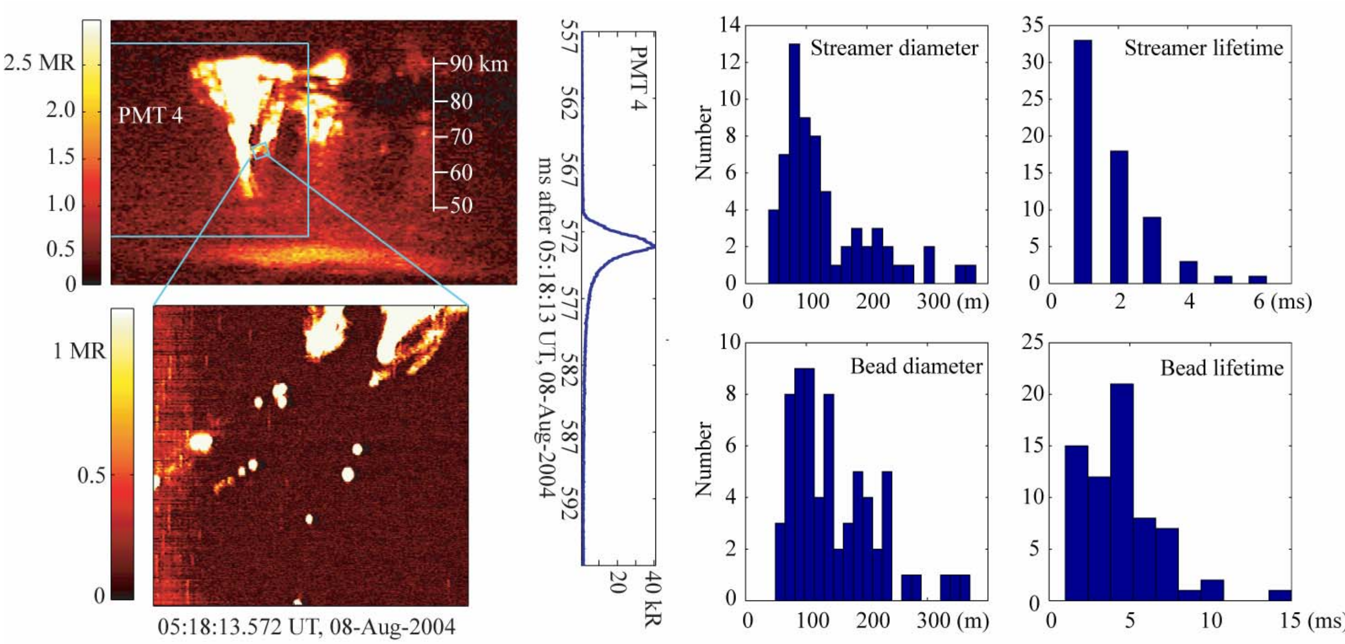

Figure 2: Statistical study of sprite features. An example of a sprite imaged in the high-speed telescopic system is shown at left. At right, distributions of bead and streamer sizes and lifetimes, over 17 events captured. Multiple features were taken from each event.

Marshall et al [2006b] used archived narrowband VLF data to study the correlation between sprites and early/fast VLF perturbations on signals propagating in the Earth/Ionosphere waveguide, following recent publications reporting such correlations (i.e., *Haldoupis et al* [2004]). A thorough study was conducted of historically successful sprite observation dates in 1995, 1999, and 2000; results showed that ~48% of sprites were observed with corresponding early/fast events, while ~61% of early/fast events had correlated sprites. This result was noted to be far from the "one-to-one" correlation reported

in *Haldoupis et al*. Furthermore, observations of possible backscattering of VLF energy from sprites is reported, in response to similar observations made in Europe (*Mika et al* [2005]). These observations, while very rare, have helped to temper the debate about such events stemming from observations in the mid-1990's (i.e., *Inan et al* [1996], *Dowden et al* [1996]).

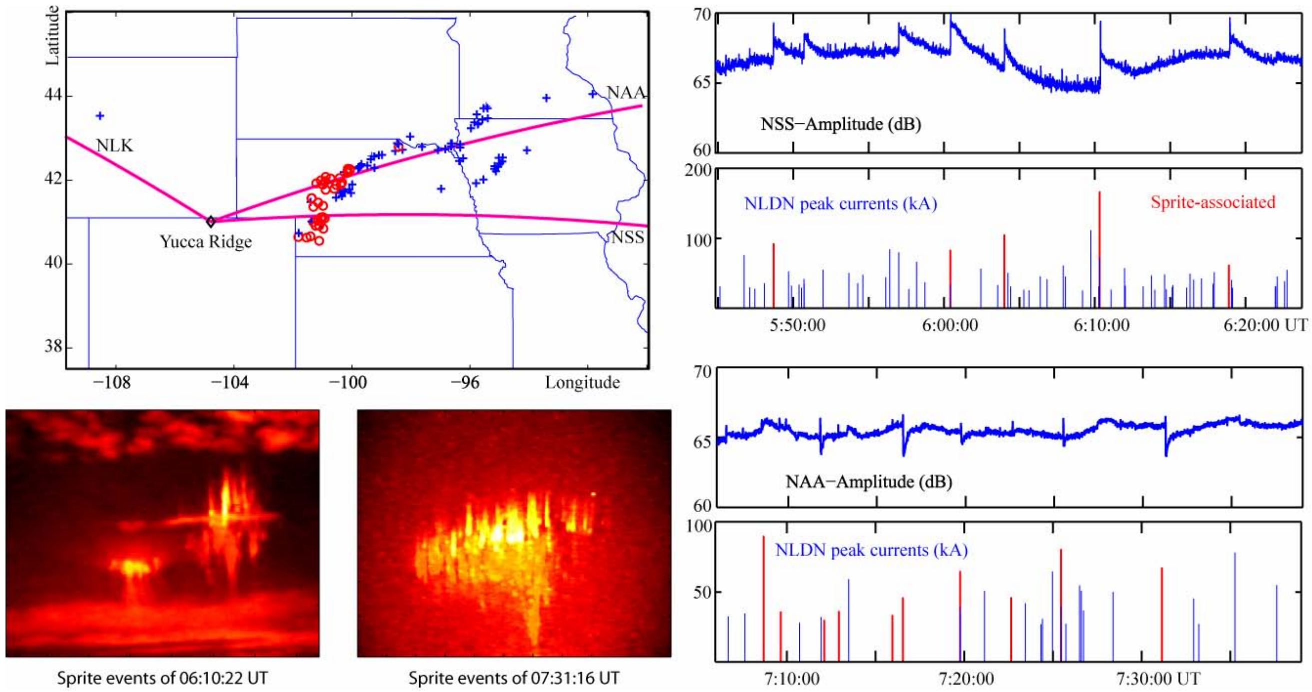

Figure 3: Sprite and VLF narrowband data from Yucca Ridge on 15 July 1995. Examples of two sprites imaged are shown at bottom left; these are summed images over a sequence of sprites occurring within less than 0.5 seconds. VLF narrowband amplitude data shows numerous VLF perturbations.

In *Peter and Inan,* [2006], two observations of LEP events recorded on HAIL are quantitatively compared to a comprehensive model of lightning-induced electron precipitation. The model consists of three major components: A model of whistler-induced electron precipitation [*Borntik et a.,* 2006a]; a Monte Carlo simulation of the energy deposition into the ionosphere [*Lehtinen,* 2001]; and a model of VLF subionospheric signal propagation [*Chevalier and Inan,* 2006]. For both cases, the model predicts VLF signal amplitude and phase perturbations within a factor of three of those observed. The model predicts a location of precipitation consistent with observations, with a slightly wider precipitation region and shorter onset delay than that observed, and accurately captures the differential delay (increasing onset delay with latitude). The modeled, precipitated energy flux (E > 45 keV) peaks at ~1 x 10-2 [ergs s-1 cm-2], resulting in a peak loss of ~0.001% from a single flux tube at L ~ 2.2, consistent with previous satellite measurements of LEP events [*Voss et al.,* 1998]. A methodology for quantitatively relating VLF signal perturbations to precipitating flux is presented. A conversion metric Ψ, relating VLF signal amplitude perturbations to the time-integrated precipitation flux (100-300 keV) along the VLF signal path, of 1.1±0.2 x 1010 [el m-1/dB] is suggested for precipitation events of similar location and characteristics to the events examined.

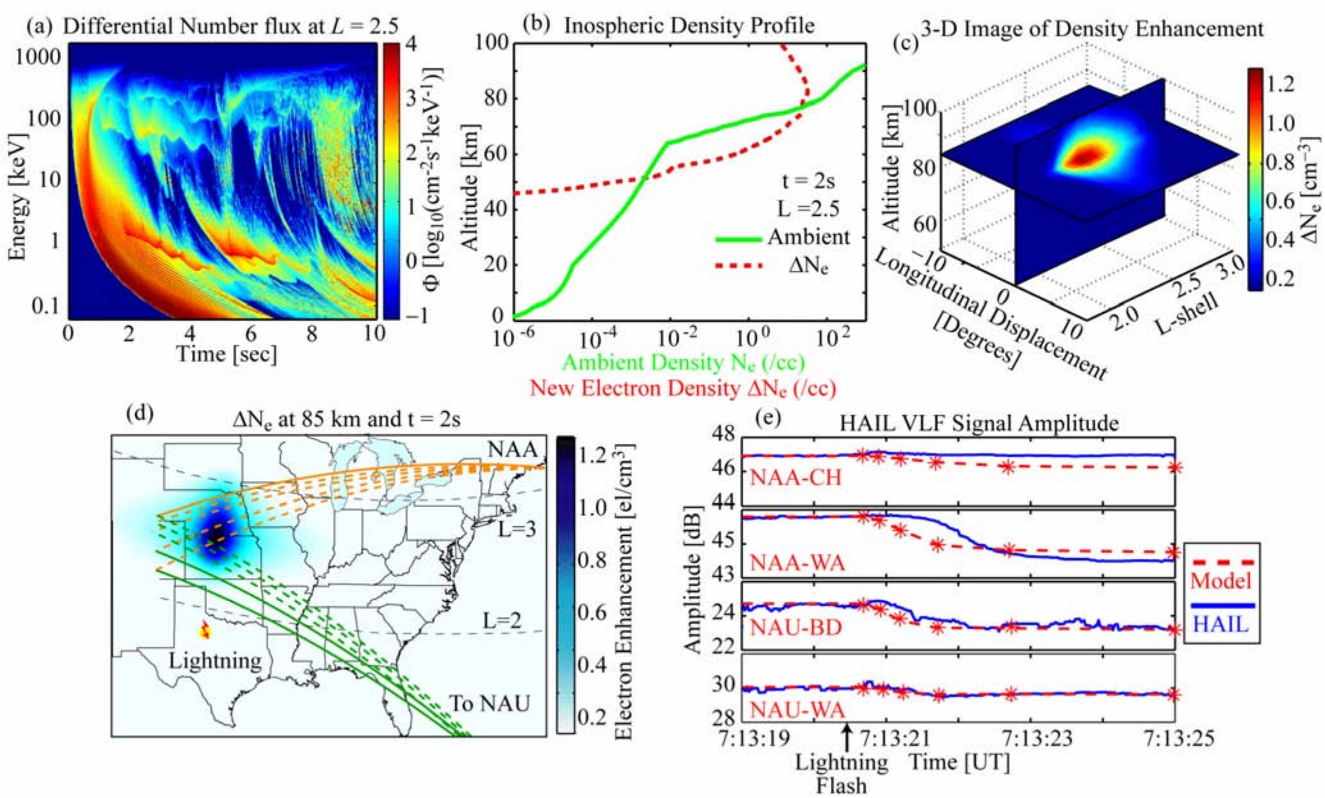

Figure 4: Precipitation flux (a) and electron density enhancement (b and c) predicted by a model of nonducted LEP. The location of the ionospheric perturbation (d) and the VLF signal amplitude perturbations (e) predicted by the model are consistent with observation.

During major geomagnetic storms, intense fluxes of precipitating electrons disturb the mid-latitude *D*-region. VLF signals recorded on the HAIL array exhibited a depression and subsequent quasiperiodic fluctuations in amplitude that persisted for several hours during a geomagnetic storm on 07 April 2000. *Peter et al.,* [2006] provided evidence that the onset of fluctuations coincide with the equatorward edge of the auroral oval extending over the perturbed VLF paths, and may be associated with variations in high-energy auroral precipitation flux onto the upper atmosphere. Given the multiplicity of paths of the proposed HAIL array, we estimated the spatial and temporal characteristics of ionospheric disturbances in correlation with supporting geophysical observations (i.e., magnetometer, riometer, and satellite data). Intercorrelation of this data is used to determine the source of the fluctuations and determine the influence of such factors as auroral electrojet location, variability of high-energy auroral precipitation, and the presence of ULF magnetic perturbations.

IMPACT/APPLICATIONS

The general impact of our results is the quantification of ionospheric variability (especially the mesosphere and the D region) due to both lightning discharges and radiation belt particle precipitation. VLF Holographic measurements with the HAIL system have led to the identification of the underlying structure and temporal and spatial characteristics of ionospheric disturbances associated with lightning discharges. In view of a global lightning rate of ~100 flashes per second, the contribution of lightning discharges may be globally important to both ionospheric variability and the possible role in the formation of the slot region of the radiation belts. Furthermore, our correlative studies of sprites,

early/fast perturbations and associated VLF activity result in quantification of the effect of sprites on the ionosphere.

TRANSITIONS

The establishment of a user-friendly web-based data viewer program (http://hailweb.stanford.edu/vlfdataviewer.html), updated daily, which allows remote access to all HAIL data and expands both our educational outreach component and facilitates our future collaborations with other researchers in the field. High school students can view 1-s resolution VLF amplitude or phase data, recorded at their host school or at any other HAIL site, and explore ionospheric effects of recent events such as solar storms, galactic gamma ray bursts, and local thunderstorms. The various MATLAB-based analysis software developed by Stanford for the HAIL research project are being used by interested high school students at the schools that house our equipment, as well as by collaborating researchers from other institutions [e.g., *Haldoupis et al.,* 2004; *Mika et al.,* 2005].

The proposed program is leveraged by our recent interactions with NSF/STC funded Center for Integrated SpaceWeather Modeling (CISM). CISM educational outreach provided support for two student engineers for one year, leading to the development of a new generation of ELF/VLF receiver system that is of high quality (sensitivity, time-resolution, and dynamic range) and low cost (<$3000), to be installed at our new sites. In addition, CISM, for its own educational outreach purposes, is deploying fifteen receivers throughout the United States, the measurements at which greatly expand our coverage.

RELATED PROJECTS

The Atmospheric Sciences Division of NSF jointly funds the holographic VLF/LF measurements component of our project. Other related projects include VLF/LF observations carried out at Palmer Station, Antarctica; University of Iraklio, Crete; Firat University, Turkey; and the Centre National de la Recherche Scientifique (CNRS) in Nancay, France, which allow us to examine characteristics of these events in settings other than over the United States.

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